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The development of an experimental method for the determination of the minimum explosible concentration of biomass powders

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ABSTRACT

Biomass powders, in both raw and thermally treated (torrefied) form, are used in 100% biomass fired or in coal co-fired plants for power generation. They pose significant fire and explosion risks during storage, handling, processing and combustion, and therefore their explosibility characteristics need to be assessed for the design of safe systems and operations. Wood biomass powders are difficult to characterise for explosibility through standard methods because of their bulky and fibrous nature. This has resulted in the lack of reliable data on the explosibility of these materials. In this study we present a new methodology – with example measurements – for the determination of the minimum explosible concentrations (MECs) of raw and torrefied wood biomass powders, using a modified Hartmann tube. This equipment can also be used as a fast screening tool for the determination of other reactivity parameters, such as flame speeds and rates of pressure rise, through which the most reactive mixture can be identified for more detailed measurements in the larger ISO 1 m^3 vessel. MEC measurements reported in this paper showed that both raw and torrefied pulverised wood biomass, were explosible at equivalence ratios as low as 0.2. This was one-third (1/3) the corresponding concentration for Kellingley coal (measured with the same method). Flame speeds 5–10 times higher than those of coal were measured for biomass. Flame speed differences will also have a direct effect on burner performance and flame stability for systems originally designed to burn coal and now firing biomass without modifications.

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1. Introduction

1.1. *Power generation from biomass fuels*

The use of renewable energy sources for power generation is increasingly raising more interest due to regulations and incentives that are being put in place by authorities with the aim of reducing greenhouse gas emissions. Biomass is one of the preferred renewable feedstocks due to its availability and its wide range of applications, since biomass can be used for the generation of transport fuels and for heat and power generation [4].

More commonly, biomass is transformed into electricity by direct combustion [5], in dedicated biomass plants or in coal and biomass co-firing plants. These processes use mainly pulverised fuels [5]. The main advantage of using biomass for power generation is that biomass can be CO_2 neutral and has a lower content of sulphur and therefore the net emissions of

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Nomenclature and abbreviations

daf	dry, ash free basis
$(dP/dt)_{max}$	rate of pressure rise (bar s^{-1}). Subscript “max” denotes maximum
F/A	mass ratio of fuel to air
FC	fixed-carbon, mass fraction of atomic carbon in the dry feedstock [1]
GCV	gross calorific value (MJ kg^{-1})
K_{st}	deflagration index (bar m s^{-1}) [2]
LFL	lower flammability limit of gases (volume fraction)
MEC_x	minimum explosible concentration (g m^{-3}) – subscripts $x = 0, 50, 100$ denote percentage probability of explosion
P_{inj}	air injection pressure (Pa)
P_{max}	maximum explosion pressure (bar, 1 bar = 10^5 Pa) [2]
S_f	flame speed (m s^{-1})
T_{max}	temperature at which maximum rate of mass loss occurs (°C)
V	volume (m^3)
VM	volatile matter, mass fraction of volatiles in the dry feedstock [3]
ϕ	equivalence ratio
ϕ_{MEC_x}	equivalence ratio at the minimum explosible concentration
ρ_{air}	density of air (kg m^{-3})

SO_2 are reduced [6], however, the process efficiency can be slightly decreased due to the lower energy density of biomass and its higher moisture [7].

Torrefaction (thermal treatment) of biomass can improve the quality of biomass as a fuel, by improving its grindability, energy density and calorific value, thereby yielding a product closer to low rank coals. In addition, transport costs are enormously reduced, which makes torrefied biomass very attractive [8].

In power generation as in many other industries where pulverised materials are used, potential explosive atmospheres can be created [9] and in order to comply with the legislation that regulates workplaces in which explosive atmospheres can be created (ATEX [10,11], DSEAR [12]), it is necessary to assess the hazards and design adequate protection and mitigation systems.

1.2. *Biomass dust explosion incidents*

In recent years a number of fire and explosion incidents have taken place which point to inadequate handling procedures and in turn to possible inadequacy of current explosion safety data for these powders;

- June, 2011 – explosion at the world's largest pellet manufacturing facility in Georgia, USA [13].
- July, 2011 – fire in Essex woodchip biomass processing plant [14].
- October, 2011 – fire at the Tyneside port which is intermediate biomass storage facility for power plant [15].
- February, 2012 – fire at Tilbury power station in the biomass storage area [16].

The above incidents, plus a number of other unpublicised events, have shaken the confidence of the industry in the handling of these new fuels, and suggest that the current practice and approach in assuming that existing explosion protection measures for coal handling systems are adequate for biomass powders, is unreliable.

1.3. *Dust explosibility characteristics*

Mitigation and protection measures for dust explosions (such as venting, suppression and containment) require the knowledge of the explosion characteristics of the powders involved [2]. Examples of these characteristics are:

- Maximum explosion pressure (P_{max}): “the maximum overpressure occurring in a closed vessel during the explosion of an explosive atmosphere determined under specified test conditions” [17].
- Maximum rate of pressure rise $(dP/dt)_{max}$: “the maximum slope of the pressure/time curve during an explosion of a dust cloud in a closed vessel” [18]. The maximum rate of pressure rise recorded for a deflagration in an ISO 1 m^3 explosion vessel is designated as K_{st} also known as *deflagration index* with units (bar m s^{-1}) obtained using the following equation:

$$K_{st} = \left({dP}/{dt}\right)_{max} \cdot \left(V^{1/3}\right) \tag{1}$$

The deflagration index is a parameter that is extensively used in the design guides for explosion vents and explosion suppression systems.

- Minimum explosible concentration (MEC): “lowest concentration of a combustible dust in mixture with air at which ignition occurs” [19]. This can be used as a measure of relative reactivity and a target concentration for “safe” operation.

According to the standards [17–19] the 1 m^3 explosion vessel is the experimental, laboratory scale, method to be used for the determination of explosion characteristics. The standards allow however for alternative methodologies which are shown to produce comparable data to the 1 m^3. In this study, a new technique is developed based on the much smaller Hartmann apparatus, for the determination of MEC and the identification of the most reactive mixture.

1.4. *Difficulties in the determination of the explosibility of wood biomass*

Fibrous woody biomass has proved to be a difficult material to characterise in the standard ISO 1 m^3 vessel [20]. The 1 m^3 vessel, shown in Fig. 1, consists of a 1 m^3 explosion chamber connected to an external 5 L dust pot where the dust is placed

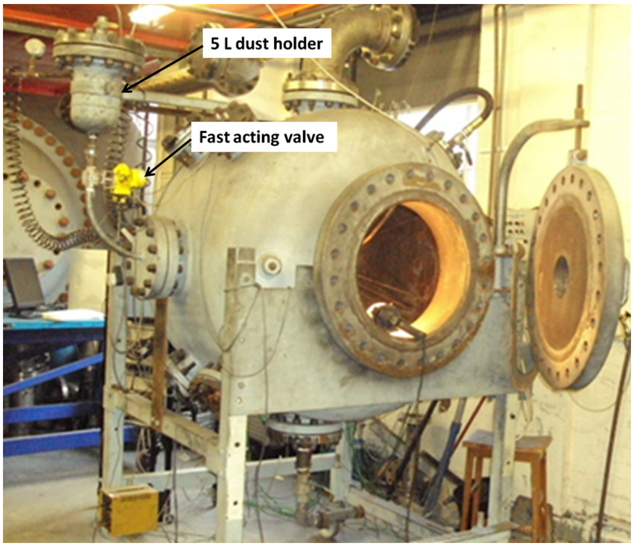

Fig. 1 – The Leeds 1 m^3 vessel – ISO method for the determination of dust explosibility [20].

and held under pressure (typically 2 MPa) prior to injection and dispersion in the main test vessel. The 1 m^3 chamber and the 5 L dust pot are connected through a pipe that has a fast acting valve that allows the transit of the dust from dust pot to the explosion chamber. When the valve opens the dust is injected inside the vessel, creating a dust cloud inside the explosion chamber that is then ignited with an ignition source (usually a 10 kJ pyrotechnic ignitor) placed at the centre of the chamber. Due to the low bulk density of biomass the 5 L standard powder holder is too small to contain the amounts needed for characterisation of the powder over a range of concentrations and it is therefore necessary to use a bigger dust holder. The most reactive concentrations of biomass powders have been found to be around 750 g m^{-3}. If for example, 750 g m^{-3} of wheat straw (which can have a bulk density as low as 100 kg m^{-3}), were to be injected in the explosion chamber, a dust pot of at least 8.5 L would be required.

The second problem arises during the actual injection process into the explosion chamber. On opening the valve on the delivery pipe the pressurised dust flows into the vessel where it branches into a semicircular pipe “C-ring” on the internal periphery of the test vessel where it disperses as a cloud into the vessel through 5 mm holes along the C-ring. Fibrous biomass cannot flow easily through the standard dispersion system since the elongated strands of wood choke the delivery pipe impeding the creation of dust cloud inside the explosion chamber. The ISO standard notes that different dispersion systems can be used.

It is therefore possible to adapt the standard apparatus to enable measurements of the explosibility parameters of biomass powders. However, it is evident that any such modifications will also alter the conditions under which the test occurs, in particular the turbulence levels in the vessel which is a critical determinant of the measurements made. It is for this reason that the K_{st} and P_{max} values of biomass powders are often over or underestimated [21,22], and flammability limits do not agree in many cases when using “standard” equipment [21]. This is what has led to a lack of reliable data of biomass explosibility.

Given the difficulties encountered to measure explosion characteristics of biomass dust clouds it is necessary to investigate the possibility of developing new techniques or modifying existing methods to facilitate the determination of explosion characteristics. This work is in progress at Leeds University [23–26] and this publication forms part of the process.

1.5. *Determination of MEC*

MECs of dust clouds appear to be affected by the vessel used for their measurement [27]; this is thought to be one of the reasons why results from different laboratories have been found to be very inconsistent [21].

Lean flammability limits (LFL) of flammable gases, (equivalent to MEC of dusts), have been very thoroughly investigated, and the limits measured are widely accepted. The method for the determination of LFL of gases uses a vertical tube with very similar dimensions as the Hartmann tube. The Hartmann tube is another laboratory scale dust explosion vessel that was used before the more recent 1 m^3 vessel was developed for the determination of explosion characteristics of dust clouds [28–33]. Other vessels have been developed over the years, such as the 20 L sphere or the Nordtest Fire 011 [27], but since the development of the 1 m^3 vessel this has been considered as the most reliable vessel for dusts. The Hartmann tube was abandoned in favour of the 1 m^3 due to a series of disadvantages, such as a weaker ignition source, lower turbulence levels, and results only applicable to ambient temperature and pressure. However, the Hartmann tube presents some advantages, such as using a much smaller volume compared to the 1 m^3 vessel which allows using much smaller quantities of material and the placement of the dust inside the vessel, therefore avoiding the delivery and density problems of woody biomass with the 1 m^3 vessel.

In this work a series of modifications were introduced to the Hartmann tube that allowed a rapid determination of MEC of biomass and torrefied biomass dust clouds, as well as the determination of additional reactivity parameters such as flame speeds and rates of pressure rise, that can be used for the identification of most reactive mixtures for further testing in the 1 m^3 vessel once the dispersion issues have been overcome.

However it should also be noted that the standard method for determining MEC in the 1 m^3 itself presents some uncertainties since laboratories often disagree in their measurements. That could be due to the fact that when using the 1 m^3 vessel, a variable amount of dust is always found inside the explosion chamber after the explosion, which causes uncertainties in the concentration of dust that actually ignited. Also, the method for the determination of MEC with the 1 m^3 seems somewhat crude: it is required to start with a concentration of 500 g m^{-3}, and then to perform tests with decreasing concentration by steps of 50% of the preceding concentration. No repeat tests are required [19]. In contrast, the method for determining the lean flammability limits (LFL) of gases requires decreasing the amount of test substance in steps no bigger than 0.2% (in absolute terms) from the concentration used in the preceding test. When the first mixture of gas and air is thus found that does not ignite, it is necessary to repeat the test at least 4 more times (without successful ignition) to conclude that such concentration does not ignite and therefore is the lean flammability limit [34].

The reason why the method for dusts is different to the one used for gases is not clear. The method developed in this work aims to follow the method for LFL on gases, which is widely accepted and gives very consistent LFL values in different laboratories and for various gases.

2. Objectives

In this paper we present part of the work at Leeds, which is aimed at developing the methodology for the measurement of the MECs of wood biomass and torrefied biomass powders using a modified Hartmann tube. The methodology aims to address the uncertainty issues in obtaining reliable and comparable MEC data for biomass. The method is under development and will be compared against literature data obtained using the standard ISO vessel and differences and deviations will be discussed.

3. Methodology

3.1. *Materials*

The materials used for the present study were two torrefied wood materials and their corresponding untreated biomass materials, Kellingley coal was also used for comparison. The two wood biomass samples and their corresponding torrefied versions were supplied in chip or pellet form by Arigna Fuels Ltd. and RWE Npower plc. Due to commercial sensitivities the authors were not provided with information on the exact type and origin of the wood, or the torrefaction process characteristics of the torrefied samples. Notwithstanding the limited information the authors believe that this work exemplifies the explosion characteristics of the wood biomass raw materials and their torrefaction products typically used in power generation. Raw biomass samples were allowed to dry in an open container for some days and then the containers were closed and remained sealed, the same as the rest of the samples. All samples were milled on a Retsch Cutting Mill SM100 with a 1000 μm bottom sieve, and separated in different particle size ranges: <38 μm, 38 μm–75 μm, 75 μm–150 μm, 150 μm–300 μm using a Retsch Sieve Shaker AS 200 Basic.

3.2. *Fuel analysis*

The fuels used for this study were characterised using ultimate and non-isothermal TGA-proximate analysis, their gross calorific values (GCV) were also determined. The ultimate analysis was performed in a Flash 2000 Thermo Scientific C/H/N/S Analyser. TGA-proximate analysis was conducted in a TGA-50 Shimadzu analyser following the temperature programs used by Biagini et al. [35–37]. For the measurement of the GCV, the Parr 6200 Oxygen Bomb Calorimeter was used.

The elemental composition in terms of C, H and O, was used to calculate the stoichiometric fuel to air ratio (F/A). The balanced combustion equation in air is shown in Eq. (2).

$$CH_yO_z + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + 3.76aN_2 \tag{2}$$

where, y and z are the atomic ratios to carbon of H and O, respectively. Substituting for a, b and c in terms of y and z, the stoichiometric fuel to air mass ratio is given by:

$$\text{Stoichiometric}(F/A) = \frac{(12 + y + 16z)}{\left(1 + \frac{y}{4} - \frac{z}{2}\right) \cdot 137.28} \tag{3}$$

Multiplying the fuel to air ratio by the density of air ρ_{air} (1.2 kg m^{-3} approximately) expresses the stoichiometric fuel to air ratio in grams of fuel per cubic meter of air, using Eq. (4):

$$\text{Stoichiometric}(F/A)(g\ m^{-3}) = \text{Stoichiometric}(F/A) \cdot \rho_{air} \tag{4}$$

Concentrations of dust in air can be expressed in equivalence ratios (ϕ), using Eq. (5):

$$\phi = \frac{\text{Actual}(^F\!/\!_A)(g\ m^{-3})}{\text{Stoichiometric}(^F\!/\!_A)(g\ m^{-3})} \tag{5}$$

3.3. *The modified Hartmann tube*

The apparatus used was a 1 L vertical Perspex tube, 322 mm long with 61 mm internal diameter mounted on a base that contains a 50 mL air reservoir connected to a line of compressed air. The compressed air remains inside the reservoir until released in order to disperse the dust inside the vessel. A remote control handset operates the ignition arc and the opening of the reservoir of air, and therefore, the air dispersion. The constant electric arc is achieved from a high voltage power supply (Fig. 2).

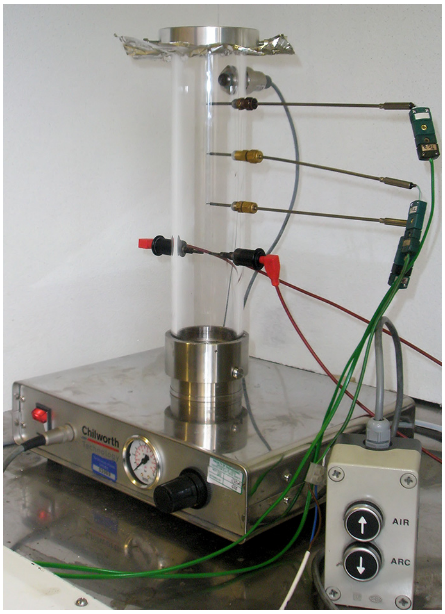

Fig. 2 – Leeds modified Hartmann tube. New method for the determination of MEC of woody biomass.

Known masses of powder were loaded into the dispersion cup. The top of the tube was always covered with a bursting vent (20 μm thickness aluminium foil secured with a locking ring), with a dynamic bursting pressure of around 55 kPa. When the tube was securely positioned vertically onto the base; compressed air was supplied to the internal 50 mL reservoir, pressurised to 0.8 MPa – see justification for this air injection pressure (P_{inj}) below. Therefore the volume of air prior to ignition inside the vessel was 1 L of air at atmospheric pressure inside the vessel, plus 50 mL of compressed air to 0.8 MPa. The total volume of air inside the vessel prior to explosion was increased under standard conditions, which was taken into account for the calculation of dust concentration. This value is the one used to express the concentration of dust inside the vessel. As an example, if 0.5 g of dust are placed in the dispersion cup, the concentration is approximately 360 g m^{-3} of air. The concentration of dust inside the vessel can be expressed as an equivalence ratio (ϕ), that is, the ratio of the actual concentration used to the stoichiometric concentration of fuel in air by mass. Thus, if the $\phi = 1$, the concentration of powder tested is exactly equal to the stoichiometric concentration (there is just enough air to react with all the fuel), whereas if $\phi < 1$, the concentration tested is smaller than the stoichiometric concentration, and therefore it is an air-rich mixture, similarly, if $\phi > 1$, then it is a fuel-rich mixture.

The modifications introduced to the apparatus included the fitting of a piezoelectric Keller PAA-11 pressure transducer to record the pressure histories during each test and three bare bead type-K thermocouples (mounted at 50 mm, 100 mm and 150 mm above the ignitor) to record the time at which the flame arrived to each of the thermocouples.

The modifications facilitated the determination of ignition of the powder at near limit mixtures rather than relying on a visual observation of flame travel beyond a critical distance, and allowed the measurement of rates of pressure rise, and the determination of flame speeds between thermocouples. These additional data, in turn, allowed the charting of reactivity with concentration and determination of most reactive mixtures for different samples, for further assessment in the 1 m^3 vessel, when the delivery issues (discussed above) are overcome.

An explosion was deemed to have taken place if the pressure rise due to the combustion reaction was ≥100 mbar, or if the flame travelled to the thermocouple fitted at 100 mm distance from the ignition source. This made the equipment similar to the EU gas LFL standard determination method [34].

The determination of MEC was achieved by testing decreasing mass of powder, repeating each experiment three times, until a concentration was found at which no ignition occurred in any of the three tests. Consequently a curve representing probability of explosion against concentration, or equivalence ratio, could be drawn. From such curve the MEC or ϕ_{MEC} could be found and defined as that concentration at which the probability of explosion is 0%, which provided the safest values. MEC or ϕ_{MEC} for 50% and 100% probability of explosion could also be determined, as shown in Fig. 3, using lycopodium powder. Fig. 3 also shows the effect of the dispersion reservoir pressure.

The Hartmann tube manufacturer recommended an air injection pressure (P_{inj}) of 0.5 MPa. This gave lower repeatability of the tests and did not allow for a clear identification of MEC since there was a wider range of concentrations for which explosions occurred only sometimes (probability of explosions higher than 0% but lower than 100%). However, higher injection pressure gave more repeatable and probably more uniform dust dispersion, decreasing the range of concentrations for which explosions occurred only sometimes, allowing thus a more accurate determination of minimum explosible concentration. Although an injection pressure of 0.7 MPa gave the same MEC results and repeatability, it was decided to use the highest air injection pressure allowed by the manufacturers, 0.8 MPa. The initial pressure conditions in the vessel were found to be consistent when the air injection pressure was set to 0.8 MPa.

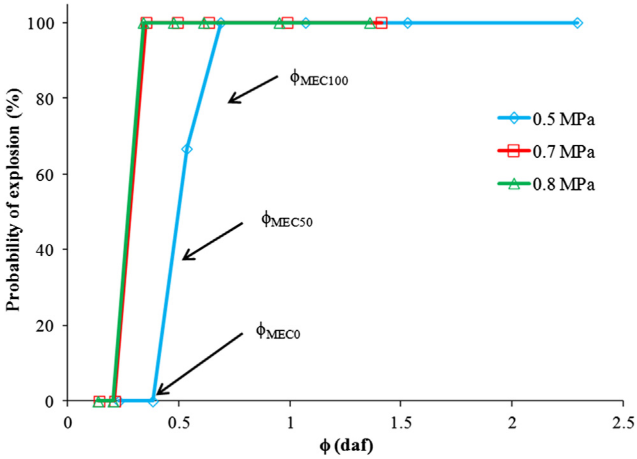

Fig. 3 – Example determination of ϕ_{MEC} for lycopodium powder as an experimental probability of explosion occurrence as a function of the equivalence ratio and the dispersion reservoir pressure.

Example pressure traces of repeat tests of a biomass sample are shown in Fig. 4, where the maximum pressure and rate of pressure rise before the vent cover bursting are also marked.

3.4. *Initial comparison of the new and the standard method for the validation of the new method*

The standard for the determination of MEC of dusts [19] states that alternative test equipment or test procedures can be used, however, for at least 10 dusts, the measurements with any other equipment or procedure shall not deviate from the results obtained using the standard vessel and procedure. It also notes that the Hartmann tube can be used for the determination of MECs if the dust is recognised as explosible. Meaning that if the dust does not ignite it does not mean that it is not ignitable, since it would possibly mean that the weak ignition source could not ignite some dusts. Biomass has proved to be ignitable, and therefore the Hartmann tube can be used. In an initial attempt to validate the results obtained with the modified Hartmann, the MEC measurements using both methods (standard 1 m^3 and modified Hartmann) of 4 dusts were compared.

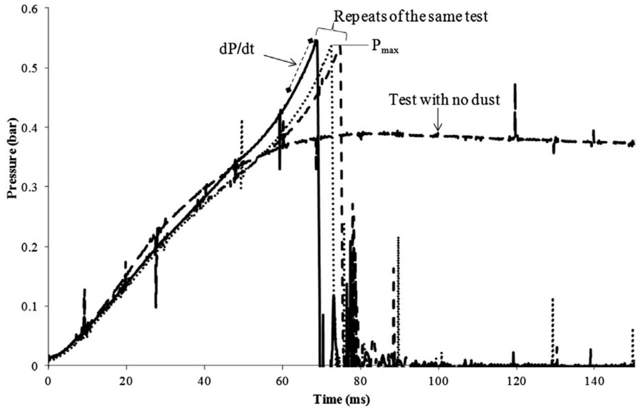

Fig. 4 – Pressure traces: study on repeatability of tests.

4. Results and discussion

4.1. *Fuel analysis*

Table 1 shows the characterisation study that includes ultimate and proximate analysis of the materials as well as the determination of heating values. The C, H and O content found through elemental analysis was used – see Eqs. (2)–(5) – for the determination of the stoichiometric F/A ratio which was then used to express the mixture of dust and air as equivalence ratio (ϕ), instead of as concentration, as this allows a more direct comparison of different biomass materials and other fuels.

Raw materials showed higher moisture and volatile matter content and lower heating values than their torrefied counterparts. Unlike the biomass and torrefied biomass samples, the coal sample contained sulphur, lower volatile matter and had a higher heating value. These features are typical of biomass, torrefied biomass and coal samples [38].

Table 1 – Fuel analysis data of raw biomass and of their torrefied (TM) versions.

Sample	Raw6	TM6	Raw7	TM7	Kellingley coal
Elemental analysis (% *w/w*)[a]					
C	42.4	49.1	44.3	64.4	51.6
H	5.5	5.3	5.7	4.9	4.4
O[b]	33.0	30.9	35.1	20.4	15.0
N	2.0	2.4	1.6	2.8	2.0
S	0.0	0.0	0.0	0.0	2.0
TGA-proximate (% *w/w*)[a]					
Moisture	9.6	3.9	10.3	2.5	2.4
Ash[b]	7.5	8.4	3.0	5.1	22.6
VM	71.9	68.9	79.0	53.5	33.2
FC	11.0	18.8	7.7	38.9	41.8
Gross calorific value (MJ kg^{-1})[a]	18.3	19.7	17.9	22.5	27.2
Stoichiometric fuel/air (F/A) (g m^{-3})[a]	182.3	166.8	184.3	131.2	126.0

a As received basis.
b Determined by subtraction.

4.2. *MEC determination and effect of particle size*

Table 2 shows the values found for MEC_0 and their corresponding ϕ_{MEC0} for the 5 materials tested (two torrefied samples and their corresponding untreated parent source and a sample of Kellingley coal), for different particle size ranges.

The raw and torrefied biomass showed lower MEC than the coal sample of the order of $\phi = 0.2$ compared to 0.7 for coal (for particle sizes less than 75 μm). Lower MEC suggests a higher reactivity and a greater hazard presented by the material, since less concentration of powder is necessary for the mixture to be ignitable. For typical hydrocarbon fuels (gases and vapours) the lower flammability limit is of the order of $\phi = 0.5$. This would suggest that the evolved gases from the biomass particles may not be hydrocarbons (such as methane) which is the usual assumption and modelling concept used for biomass, but possibly flammable gases with much wider flammability range, and in particular lower ϕ flammability limit, such as hydrogen.

Torrefied materials were less reactive than the raw biomass prior to torrefaction. According to the literature [39] (and supported by our data in Table 1) torrefied samples would be less reactive than their raw biomass material because of the lower volatile matter content. This argument is also valid for the comparison with coal. The degree of torrefaction (i.e. the treatment temperature and residence time) is also likely to influence the reactivity of torrefied materials and this is the subject of another study at Leeds. Using TGA at low heating rates it is accepted that materials that exhibit the maximum rate of mass loss at lower temperatures (T_{max}) are considered more reactive [39–41]. Fig. 5 shows the TGA rate of mass loss for Kellingley coal, Torrefied Material 7 (TM7) and its parent biomass (Raw7). According to this analysis, the raw material should be slightly more reactive than the torrefied material and more reactive than coal, since T_{max} is lower for the raw sample. This is in agreement with the relative ranking obtained from the modified Hartmann data.

The same trend was found when the MEC (expressed in Figs. 6 and 7 as ϕ_{MEC}) was measured. Raw biomass had the same ϕ_{MEC} as the torrefied sample at small particle sizes and lower ϕ_{MEC} for bigger particle size ranges which indicates that less raw material was needed for ignition, and therefore such material is more reactive. Conversely, the torrefied sample showed a decrease in reactivity.

Table 2 – MEC and corresponding equivalence ratios (ϕ_{MEC}) for a range of particle size ranges.

Dust	Particle size (μm)	<38	38–75	75–150	150–300
Raw6	MEC_0	44	37	59	96
	ϕ_{MEC_0}	0.24	0.20	0.32	0.53
TM6	MEC_0	44	37	89	163
	ϕ_{MEC_0}	0.26	0.22	0.53	0.98
Raw7	MEC_0	37	44	56	74
	ϕ_{MEC_0}	0.20	0.24	0.30	0.40
TM7	MEC_0	26	32	52	81
	ϕ_{MEC_0}	0.20	0.24	0.40	0.62
Kellingley coal	MEC_0	99	93	257	–
	ϕ_{MEC_0}	0.79	0.74	2.04	–

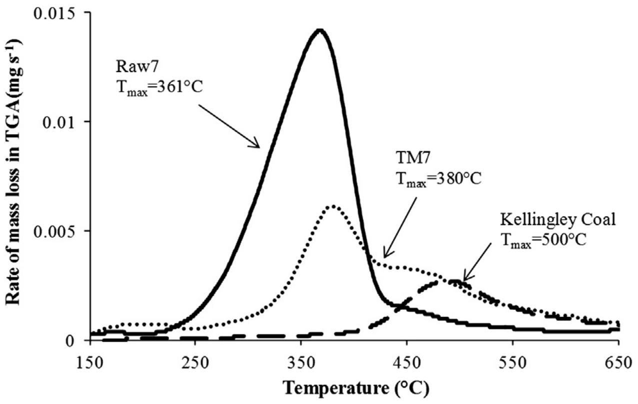

Fig. 5 – Mass loss rate from TGA test.

Figs. 6 and 7 also show the effect of particle size for different materials. Finer particle size ranges showed lower MEC or ϕ_{MEC}, indicating that finer particle size dusts were more reactive, also, in agreement with literature reports there was a limiting particle diameter below which the MEC (or ϕ_{MEC}) remained practically constant [27,42,43].

4.3. *Determination of most reactive mixture (profiles)*

The most reactive mixture, also referred to as optimum mixture, is the specific mixture of fuel and air that produces the most rapid combustion which is associated with the faster change in pressure in the system (and also maximum flame speed), and is often near to or coincidental with the mixture that produces the maximum deflagration pressure [2]. All explosion protection measures have to be designed to cope with the maximum rate of pressure change and the maximum deflagration pressure. The modifications introduced on the Hartmann tube allowed the measurement of rates of pressure rise and flame speeds which are good indicators of reactivity. Rates of pressure rise were measured using the explosion pressure histories, as shown in Fig. 4. The rate of pressure rise was calculated as the ratio of pressure increase over the last 2 ms before the maximum pressure was reached. Flames speeds were calculated through the times of flame arrival to the thermocouples situated above the ignition source at 50 mm, 100 mm and 150 mm.

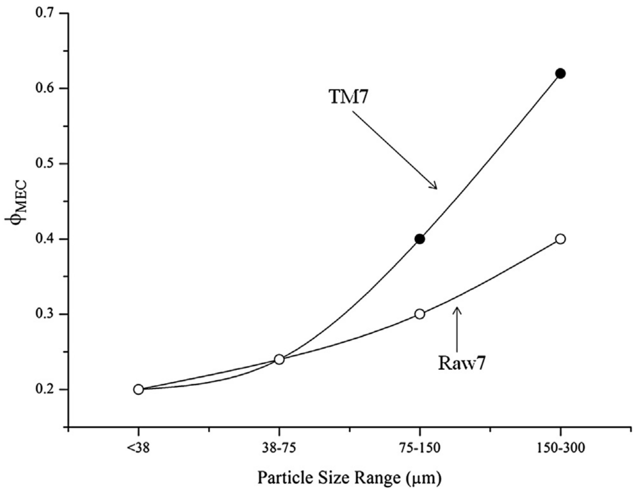

Fig. 6 – ϕ_{MEC} as a function of particle size for Raw7 and TM7.

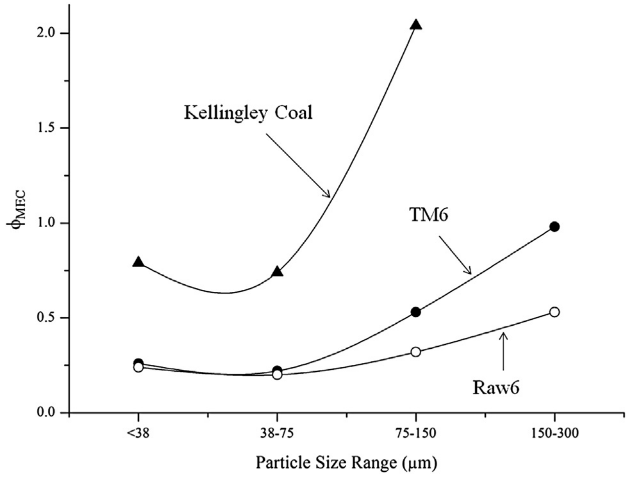

Fig. 7 – ϕ_{MEC} as a function of particle size.

Fig. 8 shows the measurements of rates of pressure rise and flame speeds for all repeat tests (and gives an idea of the repeatability of the measurements) for different mixtures of Torrefied Material 7 (38 μm–75 μm) and air. The most reactive mixture in this case (where the peak rates of pressure rise and flame speed were found) is around 1.5 times the stoichiometric value. This corresponds to the behaviour of flammable gases for which normally reactivity parameters peak at slightly richer than the stoichiometric mixtures, and decrease at both sides of that mixture. This is not generally the case for dusts where, using the 1 m^3 ISO vessel, the most reactive mixtures are usually found to be very rich mixtures [27], although no explanation is given for this behaviour. The present results using the modified Hartmann are more sensible and in line with the flammable gas data.

The rate of pressure rise can be directly related to the burning rate and hence to the flame speed and therefore it is expected (and found at least for gaseous fuels) that there is a direct relationship between the two quantities. Phylaktou et al. [42] showed a similar linear relationship for dusts strongly influenced by the type of powder. Fig. 9 demonstrates

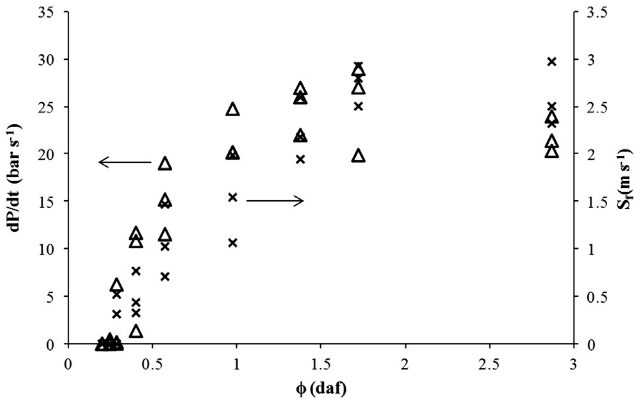

Fig. 8 – Rates of pressure rise and flame speed as a function of the equivalence ratio for TM7.

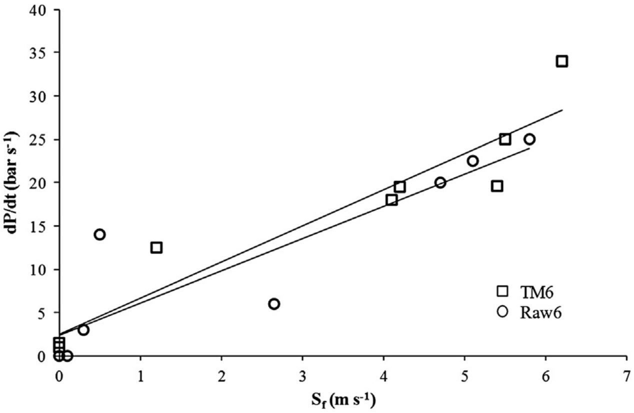

Fig. 9 – Relationship between the measured rates of pressure rise and flame speed for Raw6 and TM6.

this linear relationship between the average rates of pressure rise and average flame speeds for both untreated and torrefied material 6. This would suggest that either of these parameters could be used as a measure of relative reactivity. The data demonstrates that rates of pressure rise and flame speeds can be measured in the modified Hartmann tube and used to identify the most reactive mixtures to be tested for other reactivity parameters such as K_{st} and P_{max} in the 1 m^3 ISO vessel – if the dispersion issues for fibrous dust can be overcome. Additionally the maximum flame speeds are an important measurement that can be directly related to the burning velocity of the powder and can therefore aid the design of burners and flame stability systems.

4.4. *Summary data from the Hartmann*

Table 3 summarises the *maximum* flame speed and rate of pressure rise data for particle size 38 μm–75 μm, where they are also compared to the volatile content and the ϕ_{MEC} for the same size and also the ϕ_{MEC} for size 75 μm–150 μm. The Table shows consistency in the data from the Hartmann for the relative reactivity of the different samples. Whilst broad agreement is demonstrated with the volatile content, this breaks down somewhat when it comes to TM7 where the volatile matter is comparatively low but the reactivity as indicated by the ϕ_{MEC} and the maximum rate of pressure rise remains high. TM7 is also characterised by high fixed-carbon (FC) content shown in Table 1. Since gas–solid combustion reactions are slower than gas–gas reactions, high fixed-carbon content again suggests that the material will be less reactive. The ϕ_{MEC} and maximum rate of pressure rise for this mixture would therefore suggest that there might be other influences that cause an increase in reactivity.

4.5. *Comparison of the modified Hartmann MEC results to the standard ISO method*

The validity of MEC measurements in the modified Hartmann was tested by comparison to measurements in the 1 m^3 vessel. As it would have not been possible to obtain reliable data for wood biomass in the 1 m^3 vessel, for the reasons outlined earlier in Section 1.4, four other powders (not as bulky nor as fibrous as wood biomass) were tested in both the Hartmann and the standard vessel. The powders used were pistachio and walnut shells, lycopodium dust, and corn flour dust. All samples had particle size of less than 63 μm. Table 4 shows the elemental formulae of the powders used and the MEC results as well as the corresponding equivalence ratio of the MECs measured using both techniques.

The modified Hartmann tube gave values of MEC systematically smaller than the 1 m^3 vessel. Whilst the authors believe that the increase in injection pressure in the Hartmann to 0.8 MPa (see earlier discussion in Section 3.3) improved the uniformity of powder distribution (as evidenced by the greater repeatability of the measurements and sharper definition of MEC), it is possible that at the ignition time there might exist concentration gradients within the tube with richer areas around the spark. However, bearing in mind that, by definition an explosible mixture will propagate a significant portion of the tube and/or create significant overpressure, then sustained propagation would imply uniformity of the mixture, particularly at the lean limit. On the other hand, there are significant issues associated with the 1 m^3 vessel. As discussed earlier in Section 1.5, the standard method is crude and even with injectable powders not all powder in the pot is injected into the vessel. Also, post-test, powder is found at the bottom of the test vessel (unburnt or partially burnt) even for near lean limits where an increase in pressure has been recorded. The MECs in Table 4, from the 1 m^3, have been corrected for the actual injected mass of powder but not for unburnt material in the vessel. This would be difficult to do as by definition at the lean limit with 0% probability of ignition all material will remain unburnt, however the implication of the

Table 3 – Summary of important reactivity data with the new modified Hartmann tube method.

Sample	VM (% *w*/*w*)	Modified Hartmann data			
		Particle size 38 μm–75 μm			Particle size 75 μm–150 μm
		ϕ_{MEC}	$(dP/dt)_{max}$ bar s^{-1}	$S_{f,max}$ m s^{-1}	ϕ_{MEC}
Raw6	71.9	0.20	25.0	6.0	0.32
TM6	68.9	0.22	35.0	6.0	0.53
Raw7	79.0	0.24	21.0	2.0	0.30
TM7	53.5	0.24	25.0	2.5	0.40
Kellingley coal	33.2	0.74	6.6	0.4	2.04

Table 4 – Comparison of MEC values found using the 1 m^3 standard method and the new modified Hartmann tube method.

Dust	$MEC_{1\ m^3}$ (g m^{-3})	$\phi_{MEC_{1\ m^3}}$	$MEC_{Hartmann}$ (g m^{-3})	$\phi_{MEC\ Hartmann}$
Pistachio nut shells ($CH_{1.53}O_{0.64}$)	84	0.43	44	0.23
Walnut shells ($CH_{1.53}O_{0.56}$)	72	0.40	37	0.21
Lycopodium ($CH_{1.65}O_{0.22}$)	30	0.26	22	0.19
Corn flour ($CH_{2.01}O_{0.80}$)	113	0.53	67	0.32

unburnt powder in the test vessel in the explosible *lean* range (where all the powder should have been consumed) suggests that somehow powder settles before it has time to react and therefore the effective mass of powder participating is less than that injected and hence the effective MECs for the 1 m^3 are lower than those reported in Table 4.

The above analysis, whilst not validating the modified Hartmann tube method, casts further doubt on the reliability of the standard method measurements. In view of these results it is necessary to investigate these problem areas further and alternative validation techniques to be sought; this is the subject of further work currently at Leeds.

5. Conclusions

There are significant problems in determining the explosibility parameters of wood biomass using the standard methodologies and equipment because of the bulkiness and fibrous nature of this type of biomass, resulting in unreliable data for the design of appropriate safety systems protecting against fire and explosion.

The modified Hartmann tube was shown to produce repeatable measurements of important parameters such as the minimum explosible concentration, rates of pressure rise and flame speeds for pulverised wood biomass using small samples and achieving rapid measurement compared with the legislated method using the ISO 1 m^3 vessel. Further work is in progress to compare the results to the standard ISO vessel understand the differences and thus validate the new methodology. The results clearly show that in relative terms wood biomass is much more reactive than coal. MEC for wood biomass was found to be about $\phi = 0.2$ while in the same equipment and for the same particle size Kellingley coal showed an MEC of $\phi = 0.7$. Wood biomass reactivity was reduced when it was thermally treated (torrefied), but significant differences remained in comparison to coal. These significant differences between biomass and coal would explain the increased number of fire and explosion incidents in coal handling power plant where coal is being partially or totally replaced by wood biomass. Flame speeds 5–10 times higher than those of coal were measured for raw and torrefied wood biomass. These differences will also have a direct effect on burner performance and flame stability for systems designed to burn coal and now firing wood biomass without modifications.

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